

Applications of Deployable Telescopes for Earth-observing Lidar

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Astract- NASA's Advanced Component Technology (ACT) Program is funding the development and testing of the Deployable Optics Modeling Experiment (DOME) at the University of Colorado for developing and advancing to flight readiness high-precision deployable optics technology to enable space-based lidar measurements. In this project; precision deployment, microdynamic stabilization, and modeling technologies are verified through experiments. Long-range lidar measurements from space require efficient and high power lasers, and large collection area receivers. Large collection area receivers with diameter size >2m are needed to enable lidar measurement of key atmospheric species like ozone, water vapor, and CO₂; improve microphysical characterization of aerosols and cloud lidar systems; and for improving the performance of direct detection wind lidars. Large area deployable telescopes enable these measurements by improving the measurement sensitivity and accuracy. These systems will reduce the demand for power, mass, and volume of the transmitter; and can reduce the cost and risk of space missions. In addition, they also reduce the requirements on power dissipation and improve laser eye safety requirements (due to lower requirements on output laser power). Features of DOME will be presented along with requirements for and applications of this technology for lidar measurements from space. Lidar measurement simulations will be presented that show the improvement in the performance of lidar systems employing deployable telescopes.

I. INTRODUCTION

The Earth Science focus areas of NASA's Earth-Sun System are: Climate, Carbon, Surface, Atmosphere,

Weather, and Water. NASA's goal in Earth Science is to "observe, understand, and model the Earth system to discover how it is changing, to better predict change, and to understand the consequences for life on Earth. We do so by characterizing, understanding, and predicting change in major Earth system processes and by linking our models of these processes together in an increasingly integrated way". Development of deployable telescope technology and its application to active remote sensing will pave the way for improved observation of the Earth system from space that will provide new data to model and improve our understanding of the Earth system.

Active remote sensing by lidar has applications in all of the Earth Science focus areas.

The main advantages of using lidars for making measurements in the atmosphere is their high spatial, temporal, and spectral resolution. Because lidars are active remote sensing systems and transmit spectrally narrow laser beams, measurements can be made during day or night by using optical filters to reject the day background. Species of interest in the atmosphere are measured using tunable lasers to operate at molecular absorption features unique to the species of interest. This also permits elimination of any interference from other species and provides absolute concentration profile measurements. In general, inversion of lidar measurements is much simpler compared to passive remote sensing because of the control over the spectral characteristics of the transmitted light. Overall, the single greatest

advantage of lidars is their capability to provide high vertical resolution measurements that are generally more difficult to achieve by passive remote sensing. However, one of the main disadvantages of lidar remote sensing is the rapid reduction in the signal with range. The magnitude of the enhancement of the signal for space-based lidar systems can be appreciated by the fact that an enhancement of signal by a factor of 40^2 or 1600 is needed to replicate the performance of a ground-based system making measurements at an altitude of 10 km compared to making the same measurements from a satellite at an altitude near 400 km. This translates into the requirement for high power lasers and large collection area receivers for space-based lidar systems.

Lidar capability has been demonstrated for measurements of aerosol and cloud distributions, atmospheric winds, trace gas species, surface mapping, moisture profiling, atmospheric temperature and pressure, biomass studies, oceanic properties, chemical and biological agent detection, aviation effects and aviation safety, and planetary exploration [1]. Lidar systems have been used by NASA, NOAA, DOD, DOE, EPA, and many nationally known institutions in the US and abroad. The reason why NASA and other agencies are attracted to space use of lidars is the global coverage including oceans and difficult-to-access regions, and the excellent spatial resolution. After an initial high development and launch cost, the operational years of the mission enjoy relatively low cost because there is no large network of ground-based sensors to access and monitor and maintain.

Large collection area receivers are needed for space-based lidars in general, and Differential Absorption Lidar (DIAL) systems in particular. DIAL systems with tunable lasers are needed to measure atmospheric trace gas species. Very high power tunable lasers (output power $>5W$) are; in general; inefficient, consume large amounts of electric power, occupy large volume, require high power dissipation systems, ground observer safety issue, potentially risky, and very expensive. Large collection area receiver systems can mitigate these issues related to very high power lasers. In particular deployable telescope are very attractive because of the potential for substantial cost savings due to their smaller launch volume compared to rigid aperture telescopes. Precision deployable reflectors for space-based telescopes will be a key space engineering challenge for the next several decades. Such deployable reflectors are envisioned for a variety of missions, from Earth observation to space astronomy. Whether

they operate in IR, visible or UV, all these applications share similar requirements for extremely stable and accurate deployed configurations [2-4].

The engineering challenge is to achieve the necessary stability and accuracy for lowest overall system cost. Perhaps the most significant cost savings is realized by deploying the telescope rather than launching it in its final configuration (as was the Hubble). Most large space structures are not mass constrained but volume constrained. Deployment makes the best use of the available launch vehicle payload capacity [5].

Deployment, however, brings with it many system level trades that make the cost prohibitive if not properly considered. Deployment implies the structure is articulated in some fashion, having mechanisms that impart degrees of freedom and allow motion. The parts of the structure must move through many meters of motion, ending up within very tight tolerances, often less than a few microns of the intended position. Once deployed, the structure must hold its position, that is “remain stiff and stable,” within the necessary tolerance even under on-orbit loads [2]. This is where the critical trades interact.

The need for stiffness and stability once deployed can only be met by deployed structural “depth” that resists deformation [6-8]. In fact, the problem is not so much one of unfolding the mirror of the telescope, for that is commonly a nearly “two dimensional” kinematic problem. The major problem is deploying the deep structure that supports the mirror. That is a three dimensional kinematic problem. In other words, the stowed configuration must be expanded in all directions to achieve the final shape and function. This means more articulation in the deployment, which further increases complexity and risk. In the case of deployed radio frequency (RF) reflectors, the state of the art can deploy structures with perhaps part per 1,000 or part per 10,000 overall stability and precision [9]. In other words, a 10-meter diameter RF antenna might be deployed and stabilized to within a fraction of a millimeter to a few millimeters. This is sufficient for RF applications. But for precisions necessary for optical instruments, pushing beyond this limit requires special attention to the design of the mechanisms [10,11]. Phenomena arise below 100 microns of resolution due to the small-scale friction and anelasticity in the mechanisms and materials. This is known as “microdynamics” in the literature [12].

In this paper first we present the concept of the deployable telescope along with the objectives of

DOMÉ in Section II. In section III we present a brief overview of the optical analysis conducted by Boeing in support of DOMÉ. In section IV we describe a method for estimating lidar signals and the DIAL technique. In Section V we discuss the application of deployable telescope to Earth Science.

II. CONCEPT OF DEPLOYABLE TELESCOPE AND DOMÉ OBJECTIVES

In the late 1990's, NASA Langley Research Center (LaRC) and the University of Colorado (CU) initiated a cooperative research program to explore and develop technology for deployable lidar receiver for atmospheric science applications. This program developed both design principles and hardware for optically stable mechanisms such as hinges and latches. These principles were embodied in a deployable telescope concept developed by Composite Optics, Inc [13]. The deployed telescope concept is shown in Figure 1. The overall diameter of this particular telescope is approximately 2.5 m. A single petal of this structure was actually built. Details of the mirror and deployed structure construction can be found in [13], and the results of an initial experiment can be found in [14].

Small in overall dimension, (it was intended for a Pegasus launch vehicle), this telescope was in fact a "large space structure" from the point of view of mechanics and dynamics. Its deployment sequence is somewhat more complex than early concepts for the James Webb Space Telescope (JWST) [4]. The key advantages of this lidar design were the use of low hysteresis mechanisms and a deployed depth mirror support structure. *These two factors together meant*

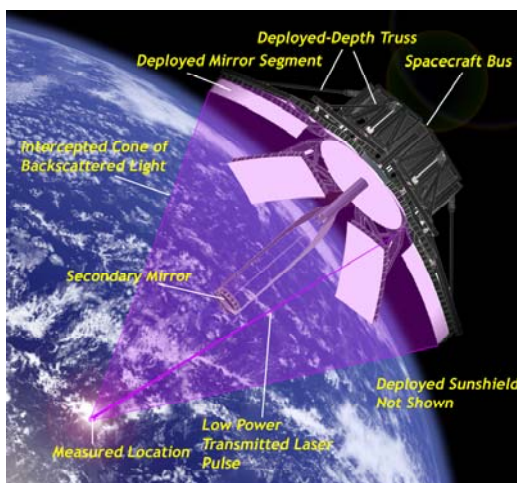


Figure 1. Concept of a space-based lidar deployed telescope

overall stability and precision of comparable JWST technology. In principal, this concept represented a substantial advancement in state-of-the-art. Whether this was to be realized remained to be proven.

In 2002, CU and LaRC proposed a program for the Advanced Component Technology (ACT) program within the NASA Earth Science Technology Office (ESTO). This project is known as DOMÉ for Deployable Optics Modeling Experiments. The overall objective of the DOMÉ project is to develop and bring to flight readiness essential component technology for the deployment of Earth observing lidar telescopes. This consists of three primary technical elements and objectives described in the next 3 subsections.

A. Precision Latching

Prior testing of the single-petal test article discovered significant deployment precision error due to the design of the latch preloading mechanism. This was reported in [14]. The objective of this project element is to develop a new latch that replaces the original latch. The new latch will have micron level intrinsic repeatability, high stiffness and low hysteresis. This is being done using the theory of mechanism development reported in [10] and [11], along with the deployment repeatability reported in [15]. A key element in this part of the project is that the performance of the latch be predictable by design analysis, not by trial and error. The models will be verified at both the component level and the overall system level.

B. Sub-System Verification of Deployment Precision and Stability

The objective of this element is to develop and implement an experiment that verifies the deployment precision and stability of the single-petal lidar test article in multiple gravity orientations. Verification in multiple gravity orientations is a common technique applied to lower precision radio frequency antennas. By showing that the deployment repeatability and stability satisfy required tolerances in orthogonal gravity orientations, it is expected this will bound the deployed shape and stability in 0-g. This depends on the predictability of the deployment mechanisms, and on the fidelity of the models. Such a measurement is also a minimum requirement to determine whether further testing in 0-g would be required for the technology. If successful, the techniques may also provide validated verification methods for deployed optical flight systems.

that this concept is perhaps 50 times the relative

C. Theoretical Modeling

The objective of this project element is to develop a theoretical model, correlated with the above experiments, which can be used for specifying requirements and tolerances on a future flight lidar system. This includes linking the model inputs to real flight conditions (including 0-g) and linking the model outputs to the actual science instrument performance. This modeling objective is essential to trace the results of the experiments to the intended application. The key challenge will be the incorporation of nonlinear mechanical and material behavior and other microdynamic effects. Also, the modeling methodology developed to meet this objective would also enable the verification of spacecraft telescopes too large to practically test on the ground. Recent progress on the DOME project is presented in the next two subsections.

D. Recent Experimental Systems Development

Progress on the DOME project has been reported earlier [16]. The DOME project experimental systems have undergone fabrication and integration during the past year. This has included the following experimental apparatus:

- Latch Component Test Apparatus – Mechanical verification of the stiffness, damping, and hysteresis models of the new high precision latch mechanism.

- Hinge Component Test Apparatus - Mechanical verification of the stiffness, damping, and hysteresis models of the precision deployment hinges.
- Single-Petal Test Apparatus – Subsystem verification of the deployment repeatability, system dynamic stability, nonlinear hysteresis, and microdynamic stability

The most challenging aspects of these experiments are their high dynamic range (100000:1) and high resolution (sub nanometer). The experimental apparatus themselves are designed to have a stability at least 10 times that of the components or test articles being studied.

E. Model Development

The DOME project modeling effort during the past year has focused on the development of nonlinear models of the mechanisms. The models exploit the fact that the deployment mechanisms were designed using ball bearings, which have predictable friction mechanics. Significant developments of the modeling effort include:

- A new nonlinear bearing element model that can be incorporated directly into a conventional finite element model for predicting structural stability and microdynamics
- Incorporation of the model into a high resolution (million-DOF class) finite element model
- Development of an explicit integration scheme for simulating the model's dynamics.

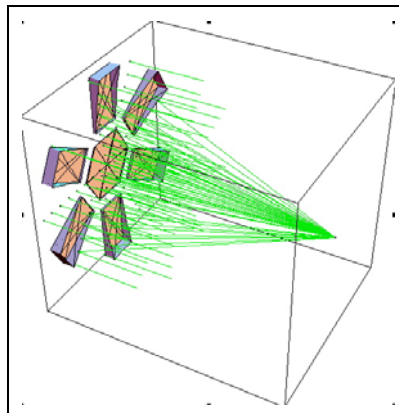


Figure 2 (a). Typical ray trace for the segmented aperture

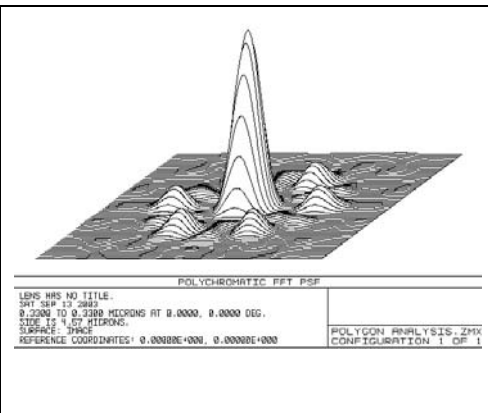


Figure 2 (b). Typical diffractive propagation of the point spread function for the segmented aperture

At the time this paper is being written, initial tests are underway to begin validating the model against the measurements produced by the experimental effort.

III. OPTICAL ANALYSIS OF DOME

The Boeing company performed optical design and tolerance analysis of DOME. The goals of this analysis were to determine the position and tilt tolerances of segments of the telescope, and the alignment of incident rays to the optical axis of the system. This effort was begun by performing both ray tracing and diffractive propagation analysis of the deployed aperture of the type shown in the Figures 2 (a) and (b). A number of criteria were used to define the level of tolerance for the optical segments [e.g. blur spot size (0.5 mm to allow accommodation of small area detectors) and Strehl ratio (0.8)].

Both spherical and parabolic primary mirror segments were considered. Consideration of a spherical segment was included in the study since DOME has a full-sized sample of such a mirror and is investigating its dynamic properties. The performance of a telescope using such a mirror encouraged us to also consider designs using a parabolic primary mirror, whose mechanical properties would be close to those of the spherical segment already in hand.

If a spherical primary mirror were to be used for imaging, designs involving four mirrors are required, and were designed during this study.

In all cases, the field of view of the designs is quite limited. For those rays entering the system at angles of about 0.4 degrees (~7 mrad, half angle), significant aberrations are present. These aberrations may not be a problem for a 'light bucket' design, such as might be considered for a direct detection receiver. For imaging systems a more satisfactory solution is to limit the field of view to that which is required by the science. For these small fields of view, quite adequate imaging can be achieved as measured by the size of the focal spot diagram and the diffractive point spread function.

IV. LIDAR SIGNALS AND THE DIAL TECHNIQUE

A. DIAL modeling performance estimates

The lidar signal P (photo-electrons per range bin) is calculated using the lidar equation:

$$P = \frac{E}{h\nu} \cdot O_E \cdot Q_E \cdot \frac{A}{R} \cdot (B_M + B_A) \cdot \Delta R \cdot e^{-2(\beta_M + \beta_A) \Delta R} \quad (1)$$

for situations in which the spot diameter in the atmosphere is smaller than the lateral extent of the receive field of view at the operating range. When the beam size in the atmosphere is larger than telescope field of view at the same range, the same equation is used, but the signal decreases as $1/R^4$. This can occur, for example, if the same optic is used to both project and detect the beam. If, in addition, multiple pixels are used to form a lateral image of the atmosphere, each pixel will have a field of view smaller than the projected beam and the signal will decrease as the 4th power of the range. Where E is the laser pulse energy, $h\nu$ is energy per photon, O_E is the optical efficiency of the receiver, Q_E is the quantum efficiency, A is the effective area of the receiver, R is the range from the lidar to the measurement location, ΔR is the range resolution, B and β are backscatter and extinction coefficient profiles respectively for molecules (M) and aerosols (A). This equation relates many of the lidar and atmospheric parameters to the detected signal and is very useful in conducting some of the trade-off studies. The detector noise is calculated using:

$$D = \frac{NEP}{\sqrt{2}} \cdot \eta \cdot \frac{\lambda}{hc} \cdot \Delta t \quad (2)$$

Where NEP is the detector noise equivalent power, η the quantum efficiency, λ the wavelength, h the Planck's constant, c the velocity of light, and Δt the sample time. Full-moon background was used to predict the performance for all night observing conditions. DIAL measurement simulations were conducted using the methodology given in [17].

In the DIAL technique two spectrally close laser pulses are transmitted near simultaneously with one pulse called the "on-line", at a strongly absorbing spectral location due to the presence of an absorbing gas and another, called the "off-line", at a less absorbing spectral location. In principle, concentration profiles of the absorbing gas can be retrieved using the on- and off-line lidar signals and the knowledge of the differential absorption cross-section ($\sigma_{on} - \sigma_{off}$) [18]. The advantages of the DIAL method are: high vertical resolution measurements, absolute concentration profiles of constituents without a need for calibration, laser wavelength selection permits isolation from other species, measurements can be made during day or night, direct inversion of species profiles with few assumptions or initial guesses, simultaneous aerosol

profiles and cloud distributions are obtained. Overall, the greatest advantage of using lidar remote sensing is the capability to provide vertical profile information. In addition, active remote sensing provides an anchor and validation to total column burden retrievals from any passive measurements. The DIAL technique has been used successfully to measure a large number of trace gases in the atmosphere from laboratory, ground, and aircraft [19]. The DIAL technique has been employed most successfully for atmospheric ozone and H_2O measurements in field campaigns and monitoring [20, 21]. The technology challenge is to build DIAL/lidar systems for operation from space that require large collection area telescopes in an environment of cost restraints.

V. APPLICATION OF DEPLOYABLE TELESCOPE TO EARTH SCIENCE

Tropospheric chemistry is considered to be the next frontier of atmospheric chemistry, and understanding and predicting the global influence of natural and human-induced effects on tropospheric chemistry will be the next challenge for atmospheric research over the foreseeable future. In the troposphere, trace-gas species of interest include ozone, OH, NO_x (NO and NO_2), CO , and some hydrocarbons; and aerosols and clouds. In particular, atmospheric ozone is one of the key tropospheric chemistry species because of its influence in many atmospheric processes. Active remote instruments that can provide vertical profile measurements of ozone can lead to better understanding of such atmospheric phenomena as: the production, distribution, and loss of ozone,

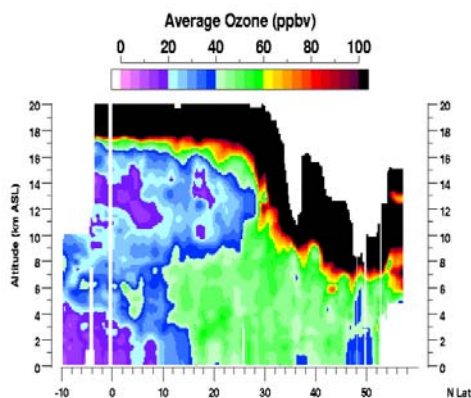


Figure 3. Latitudinal variation of ozone over the western Pacific from airborne DIAL observations during February-March 1994 [19].

anthropogenic pollution, biomass burning, atmospheric transport and dynamics, photo-chemical

processes in the atmosphere, stratospheric-tropospheric exchange, atmospheric climate and radiation, and influences of atmospheric lightning. Knowledge of these phenomena is needed to evaluate the effects of chemical changes on the global hydrological cycle, the cycling of nutrient compounds through the earth environment, the accumulation of greenhouse gases, the acidity of rain and snow, and the formation of ozone in the troposphere.

Tropospheric ozone is not uniformly distributed and it exhibits considerable vertical stratification and fine horizontal structures that contain information on the origin and age of this important species. Likewise, the altitude distribution of upper tropospheric ozone is a critical parameter in climate models. Temporal and horizontal variability is also important, including significant diurnal variations. An example of the measurement of ozone in the lower atmosphere using an airborne UV DIAL system is given in Figure 3. These data are a composite of measurements taken during a series of flights over the Pacific in 1994 and they show the variation of ozone from 10° S to about 60° N. This figure demonstrates the capability of ozone to map many dynamical features like the latitudinal variation of the tropopause (the region that transitions from the high stratospheric ozone to lower ozone in the troposphere), low ozone in the tropical lower troposphere, low ozone transported to high altitudes by convection, and mid-latitude enhancement of ozone below 7 km due to photochemical production of ozone from pollution and from stratosphere-troposphere exchange. The detailed requirements for space-based ozone measurements are specified in [22]. Measurements with horizontal resolution of 200 km and vertical resolution of 2 km at 10% measurement accuracy are required to capture regional and continental scale processes. Such a capability would enable analysis of main chemical and dynamical processes evident in Figure 3. A measurement simulation to capture the broad scale atmospheric features is shown in Figure 4. A mid-latitude atmosphere and US standard ozone model profile were used to compute the on- and off-line signals. The lidar parameters used in the simulation are: Laser energy 500 mJ/per pulse, pulse repetition rate 10 Hz, an optical efficiency of 65%, and a detector quantum efficiency of 31% are assumed. Figure 4 shows the measurement error profiles of DIAL systems with a conventional 1.35m diameter telescope and several deployable telescopes. Clearly, the conventional telescope configuration is unable to provide the required measurement accuracy of 10%, deployed telescope apertures of ~ 5 m are needed. The

current DOME design enables this class of deployable telescope development.

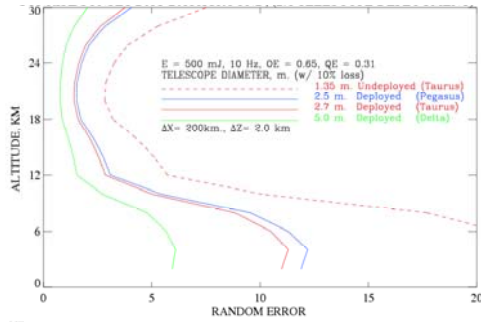


Figure 4. Space-based UV-DIAL ozone measurement simulations from 350 km altitude.

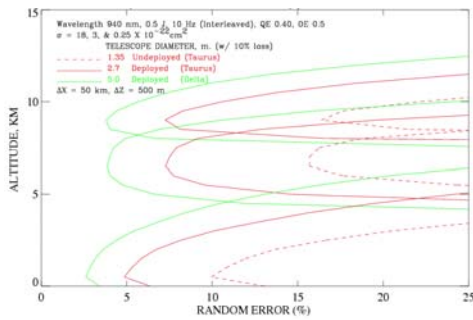


Figure 5. Space-based DIAL water vapor measurement simulations from 350 km altitude.

Water vapor in the atmosphere is the most important trace gas element because of its influence in many of the atmospheric processes including radiation and climate, meteorology and severe storm, dynamics and transport, chemistry, and optical and IR transmission. Water vapor is a key element in the global hydrologic cycle, and it plays a critical role in our understanding of the processes which govern weather and storm phenomena, i.e., evaporation, cloud formation, precipitation, and the release of latent heat. Measurements with airborne DIAL systems have been used to show that accurate, high-resolution measurements of water vapor have had significant, positive impacts on forecasts of hurricane track and intensity [23]. However, water vapor has large variations with altitude, latitude, and season and is still poorly quantified over vast regions particularly in the upper troposphere from current observations. Measurement capability of space-based DIAL systems for profiling water vapor is shown in Figure 5. The lidar parameters used in this simulations are: laser wavelength 940 nm, pulse energy 500 mJ, repetition rate 10 Hz, receiver optical efficiency 50%, and detector quantum efficiency 40%. Figure 5 shows that DIAL systems employing conventional 1.35m diameter telescope size is unable to provide

either the coverage needed or the accuracy. Deployable telescope with aperture of 3m and larger can meet the coverage and accuracy requirements of profiling water vapor.

Atmospheric CO₂ is a key component of global carbon cycle. It is a major contributor to climate forcing and change. However, its sources and sinks are uncertain and the temporal variations are not well documented. DIAL profiling from space with the required accuracy of ~1-2 ppm can revolutionize the knowledge of the variability of CO₂ and its association with sources and sinks. A number of NASA programs, including the Laser Risk Reduction Program, ACT, and IIP are contributing to the development of the capability for DIAL measurement of CO₂ from space. Deployable telescope technology is one of the key enabling technologies for these future space-based DIAL systems. Deployable telescope technologies are also applicable to other direct detection lidar systems including the development of advanced aerosol lidar systems like the High Spectral Resolution Lidar (HSRL), direct detection winds, and laser altimeters. A roadmap for the development of future aerosol and DIAL systems is shown in Figure 6.

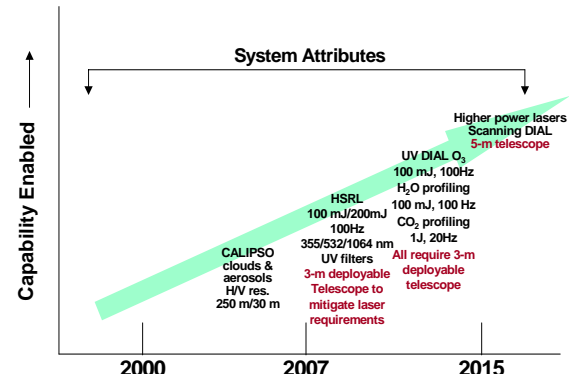


Figure 6. Roadmap for future space-based HSRL and DIAL technology developments.

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